Office of Naval Research International Field Office

30. Nanostructured Al-Fe Alloys

Dr. Jun Kameda

July 17, 2003

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http://www.onrifo.navy.mil
or Email: *kamedaj@onrasia.navy.mil*

Contents:

***Key Words**: Nanostructured Al-Fe alloys, Strain rate effect, Hopkinson-bar tests, Electron beam deposition method, Super-saturated solid solution*

1. Summary

Prof. Mukai has expertise in studying superplasticity and dynamic deformation behavior in nanostructured lightweight materials. He was an invited presenter at the TMS-Spring Meeting in San Diego CA, visited Boston MA and Washington DC under the Visitor Support Program (VSP) of the ONRIFO on March 2-14, 2003. One of his VSP objectives is to seek U.S. collaborators for a NICOP proposal. He has presented his work on nanostructured Al and Mg alloys to Dr. Vasudevan, Scientific Officer of Materials S & T Division (ONR 332). He has maintained collaborative efforts with Prof. Suresh since he spent a year at MIT as a visiting scientist. This report contains his presentation summary.

2. Background

Nanostructured metallic and ceramic materials have unique mechanical properties. Currently numerous programs attempt to tailor advanced structural and functional nanostructured materials. Mukai's group has developed high strength (650-850 MPa) Al alloys by applying an electron beam deposition (EBD) method to achieve super-saturated solid solution of Fe, leading to to the formation of nano-sized grains. The nanostructured Al-Fe alloys show stronger dependence of strength on the Fe content and weaker dependence on the strain rate, compared to other ultra-fine grained Al-Fe alloys.

3. Assessment

The application of the EBD method enables to fabricate high strength Al-base alloys. While the applicability of such alloys is restricted in functional components due to the size limitation, such a study will provoke scientific interests.

4. Points of Contact

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Information
@ONR Headquarter
March 12, 2003

Controlling grain size and texture to develop a tough solid solution nano-crystalline aluminum alloy

Toshiji Mukai

Research Center for Advanced Science and Technology,
The University of Tokyo, JAPAN

Motivation

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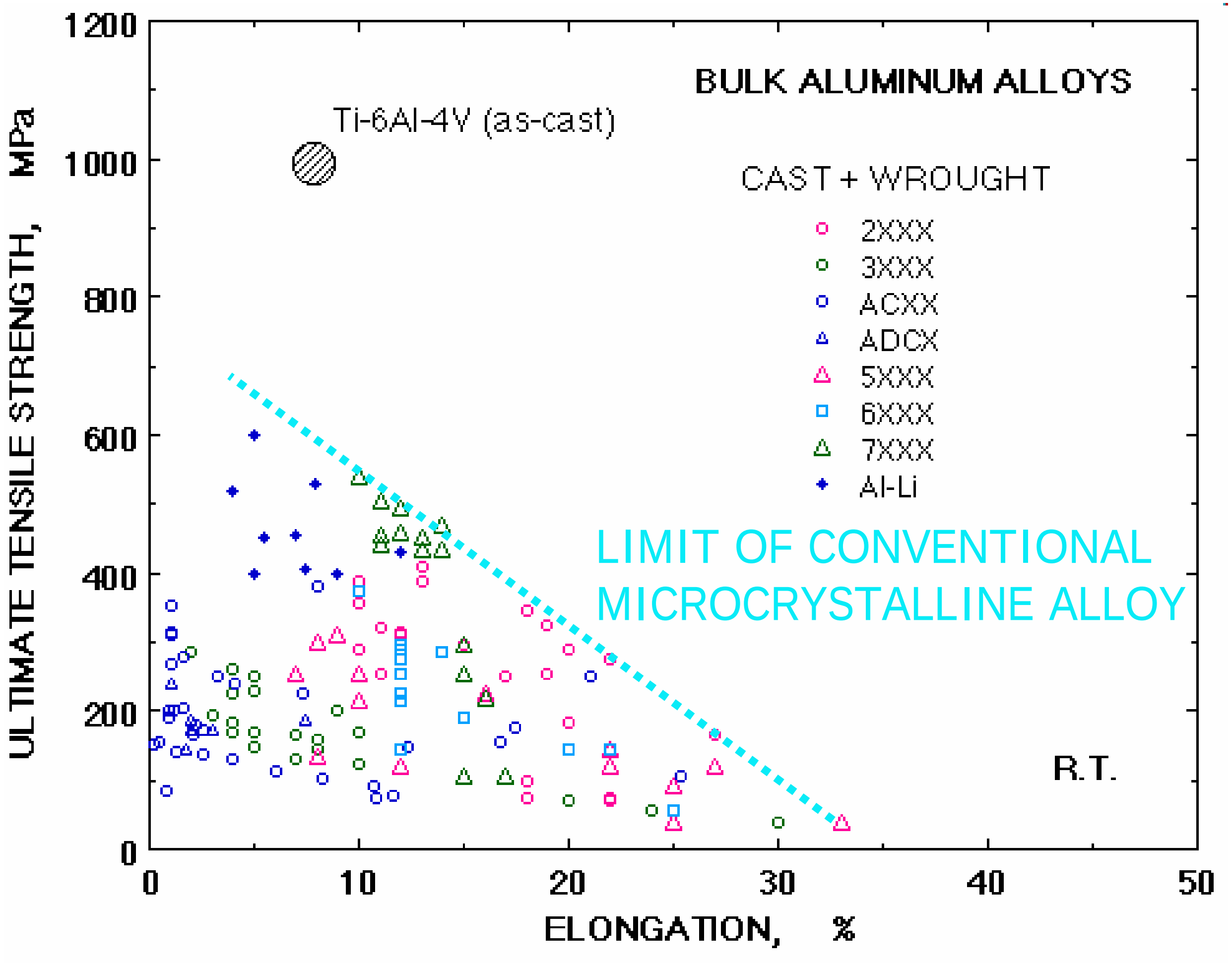
RCAST,
Univ. Tokyo

- Replace Ti alloys to Al alloys for the weight reduction(- 40%) in future Aerospace Application.
- However, conventional Al alloys does not show sufficient strength and ductility balance.



Previous Works of Grain Refinement in Bulk Aluminum

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RCAST, Univ. Tokyo

- Developed by Advanced Technique
  - Powder Metallurgy(P/M)
  - Mechanical Alloying(MA) +P/M
    [Al-Mg-Li, *d*~800nm]
  - Crystallization of Amorphous Powder +P/M
    [Al-Ni-Mm, *d*~70 nm]
  - Consolidation of Nano-crystalline Powder +P/M
    [Al-Ni-Mm-Zr, *d*~100 nm]
  - Physical Vapor Deposition(PVD)
  - Severe Plastic Deformation
    - Torsion Straining
    - Equal-Channel-Angular-Extrusion(ECAE)
      [Al-Mg-Mm, *l*~220 nm]

Strength-Ductility Balance in Advanced Fine-Grained Al Alloys

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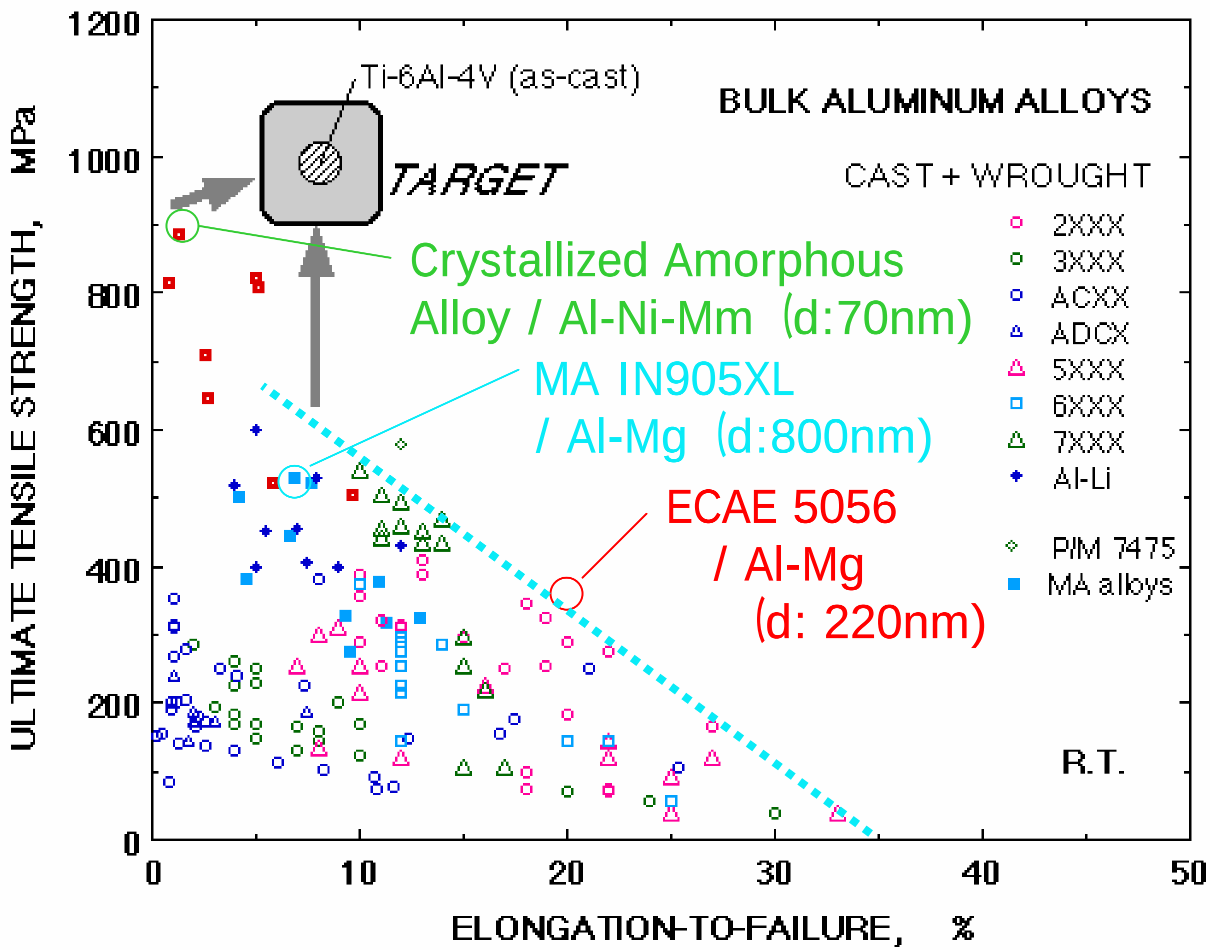

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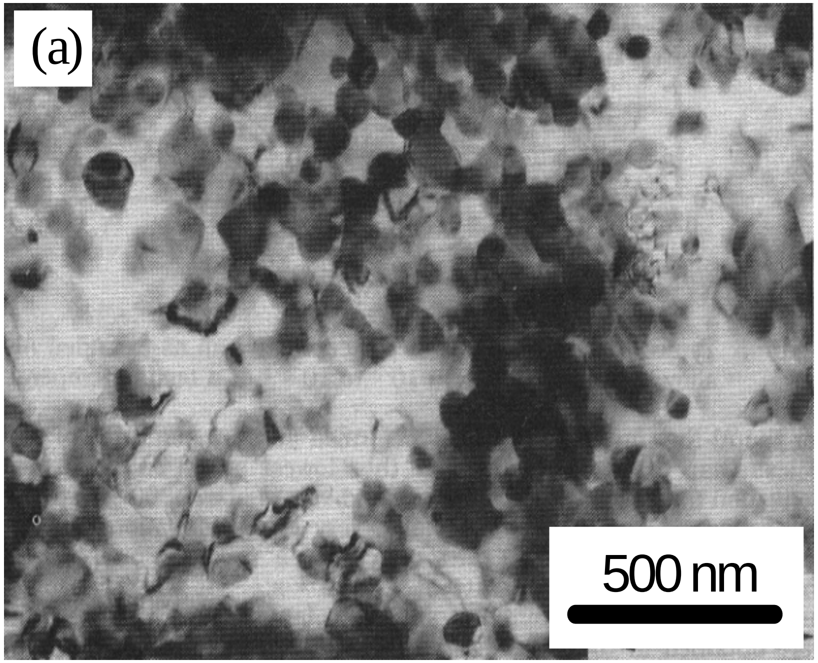
Typical Microstructure of NC alloy crystallized from Amorphous Powder

[Al-14wt.% Ni-14 wt.% Mm, Crystallized from Amorphous]

(Supplied by YKK Co., Japan)



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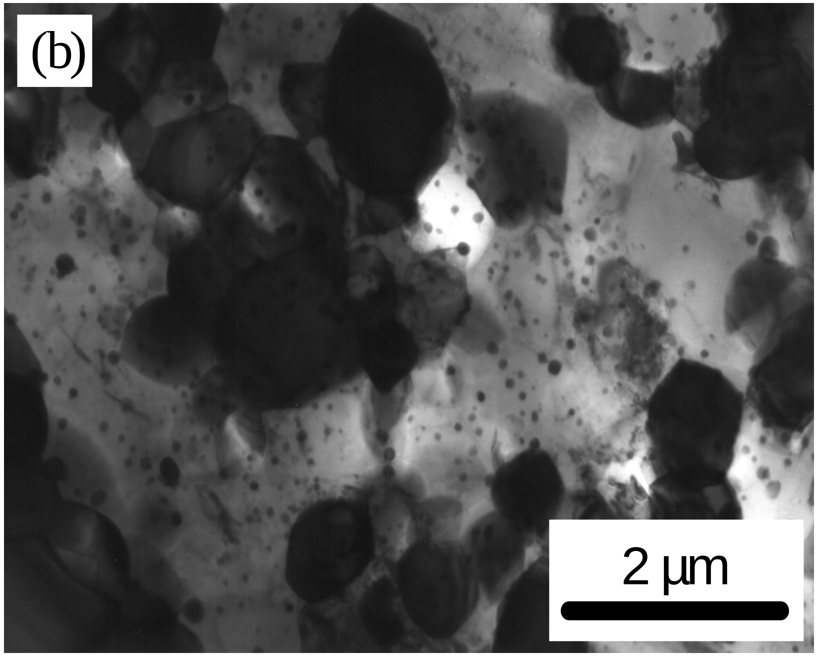

[Annealed at 773 K]

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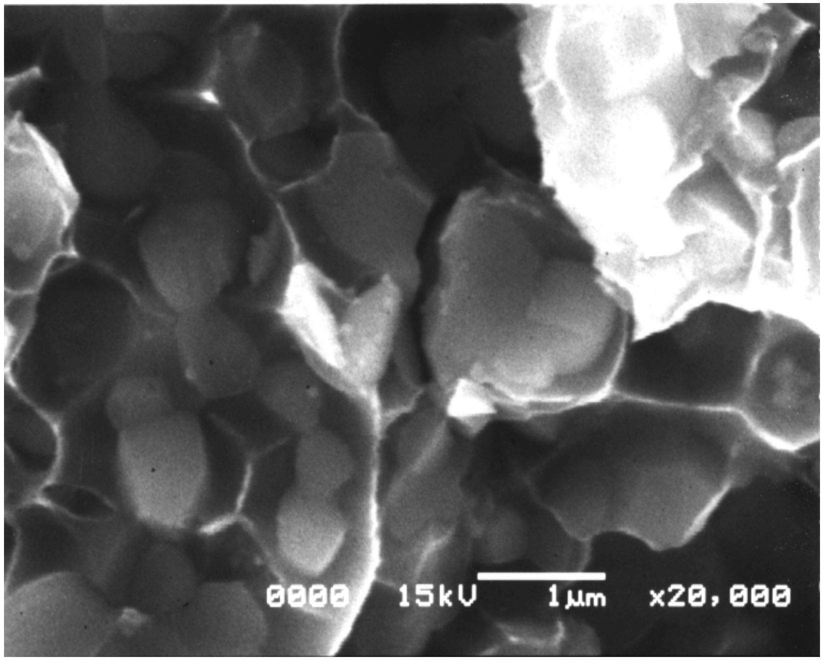
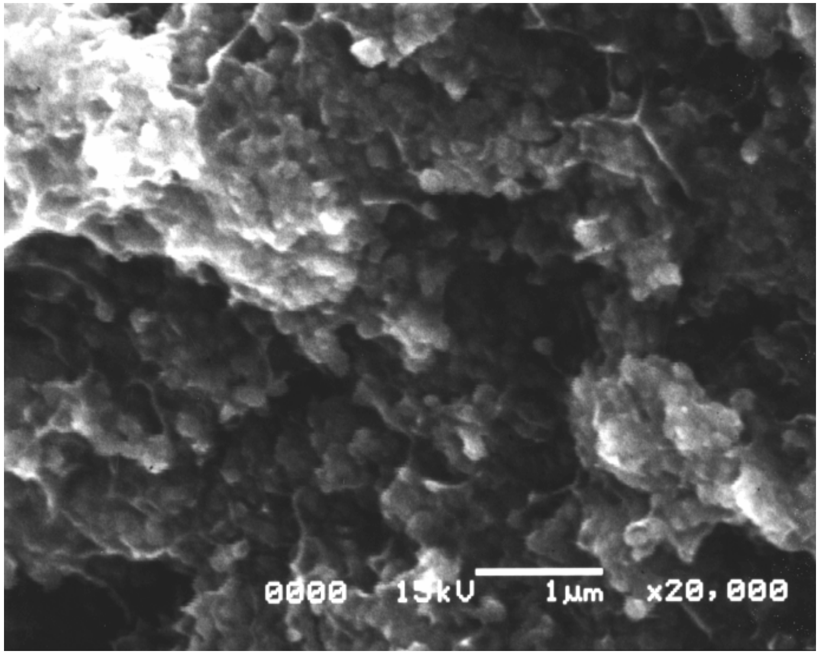
Fracture Feature

- Al-Ni-Mm Alloy (Crystallized from amorphous powder)
- At dynamic strain rate (10^3 s^{-1})

[d = 1 μm] *[d = 70 nm]*





[Elongation-to-Failure: 0.6%] *[Elongation-to-Failure: 1.2%]*

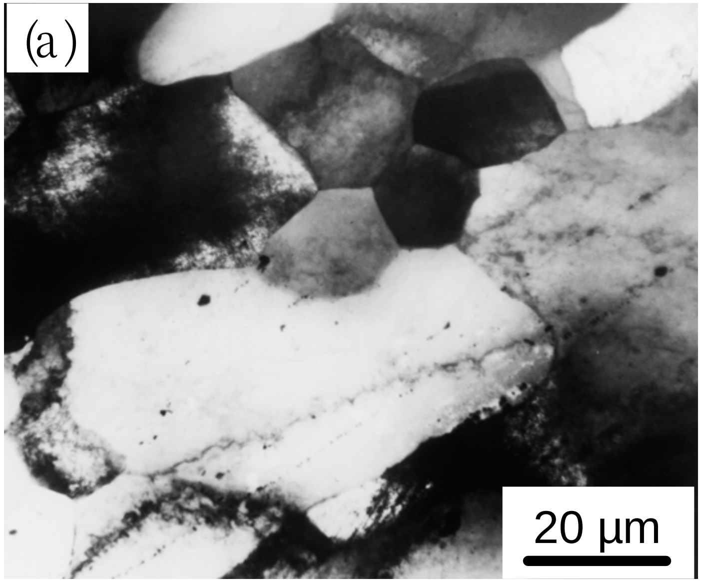
- Brittle Fracture --- at the interface of Matrix/Second Phase
- Elongation-to-Failure increases with Grain Refinement

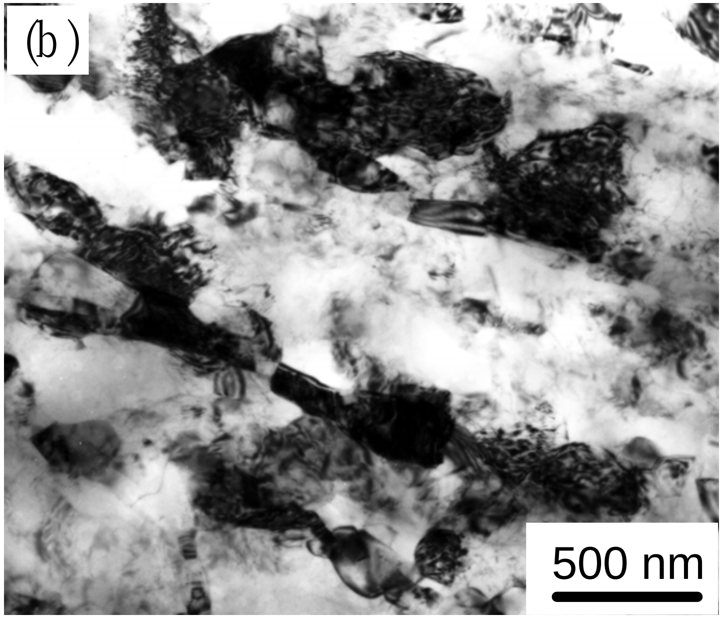
[Mukai, Higashi: Scripta mater. (2000)]

Typical Microstructure of SMC alloy through ECAE

Toshiji Mukai
RCAST, Univ. Tokyo

- Material: 5056 Al Alloy
  [Al-4.8Mg-0.07Mn-0.06Cr -0.1Fe-0.06Si, wt.%]
- Grain Refinement:
  ECAE (Equal-Channel-Angular-Extrusion) Process
  - (a) Fully Annealed [d = 35 μm]
  - (b) ECAE Alloy [l = 220 nm]
  - (c) ECAE+Annealed [l = 1 μm]
  - (d) ECAE+Annealed [d = 10 μm]





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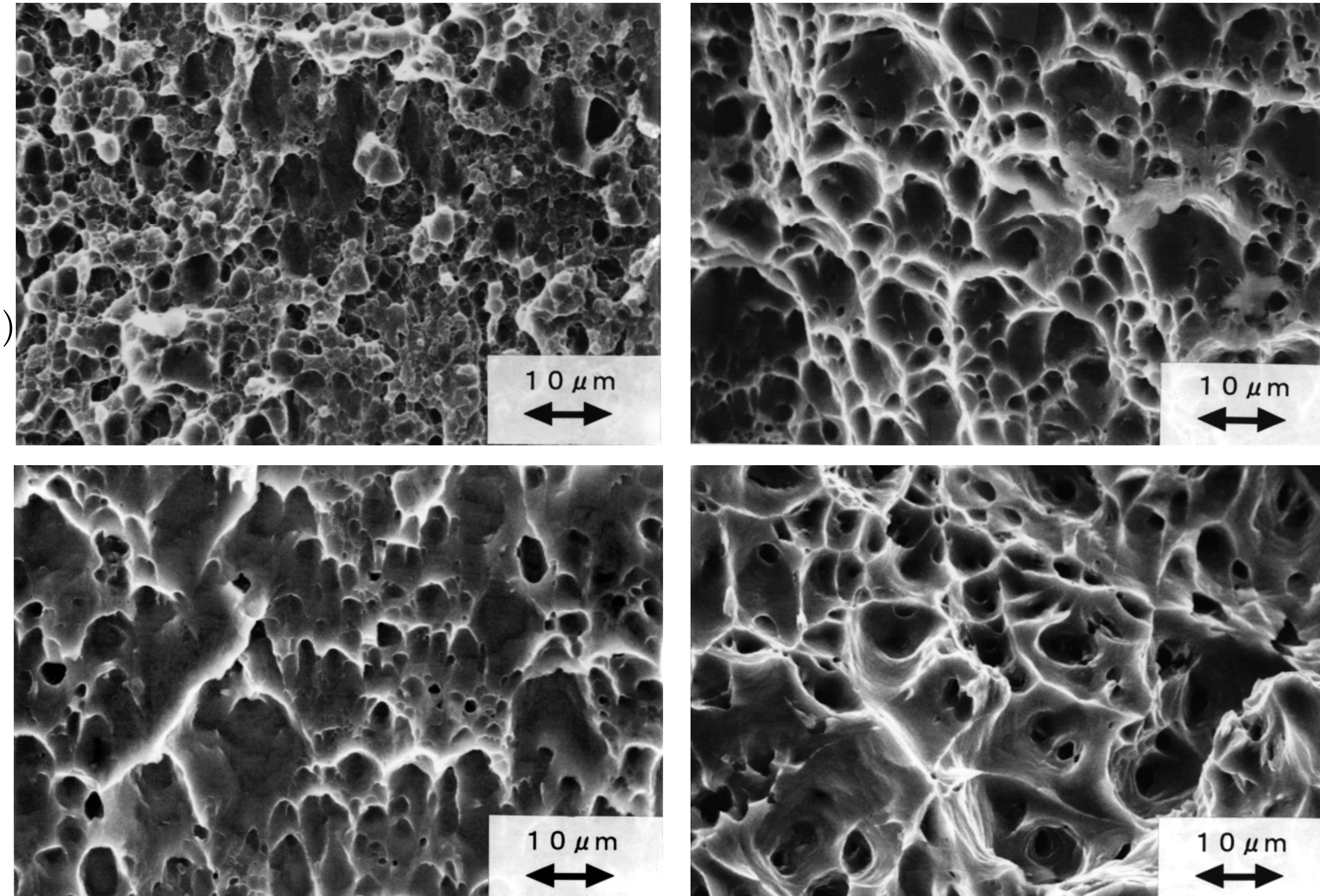
Fracture Feature

Quasi-Static (10^{-3} s^{-1}) | Dynamic (10^{3} s^{-1})

5056-ECAE (0.22 μm)

5056-0 (35 μm)



Variation in Elongation with Refining Grain Size for Bulk Aluminum Alloys

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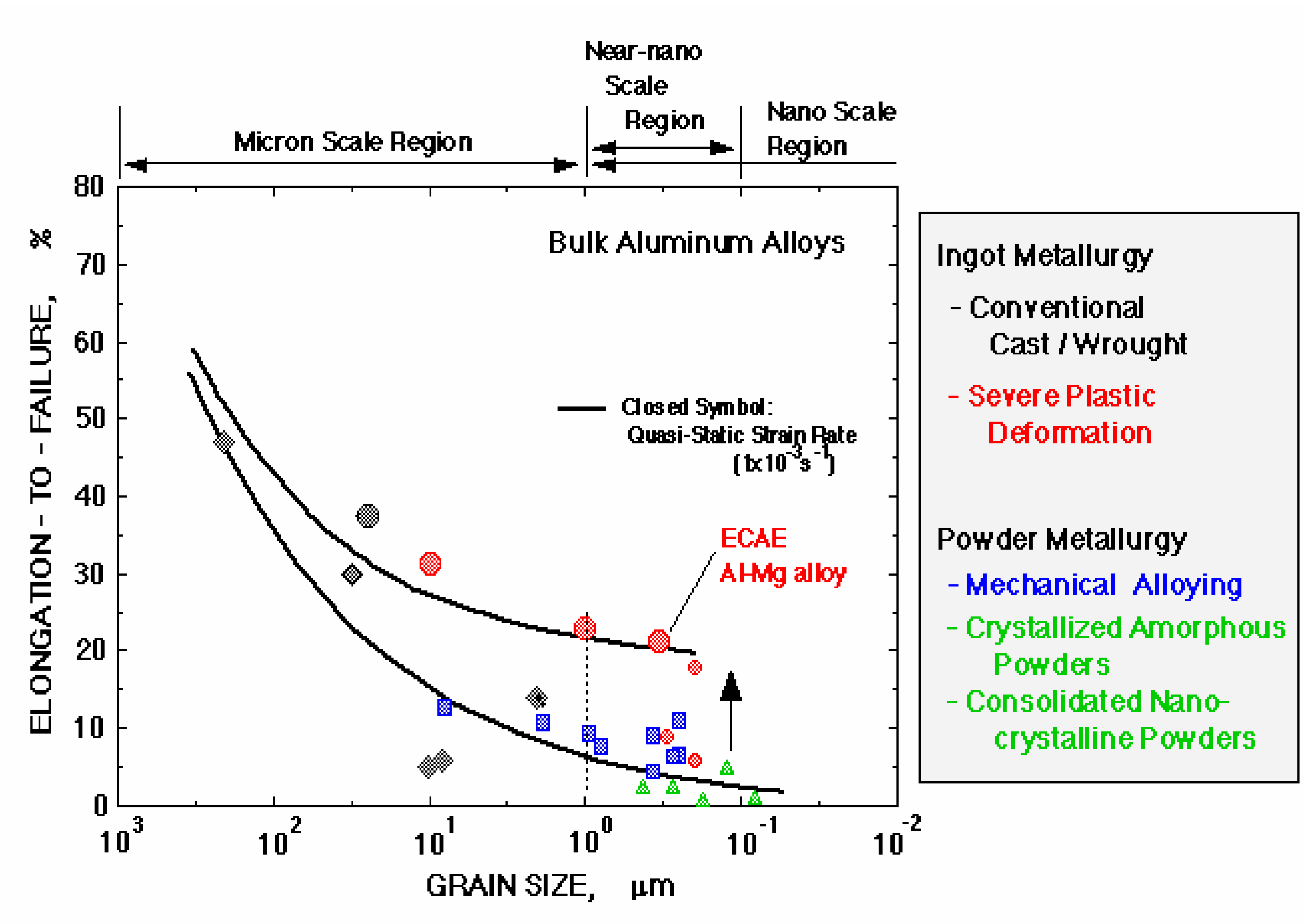
Univ. Tokyo



- Possibility of nano-crystalline/solid solution alloys

Variation in Elongation with Refining Grain Size for Bulk Aluminum Alloys

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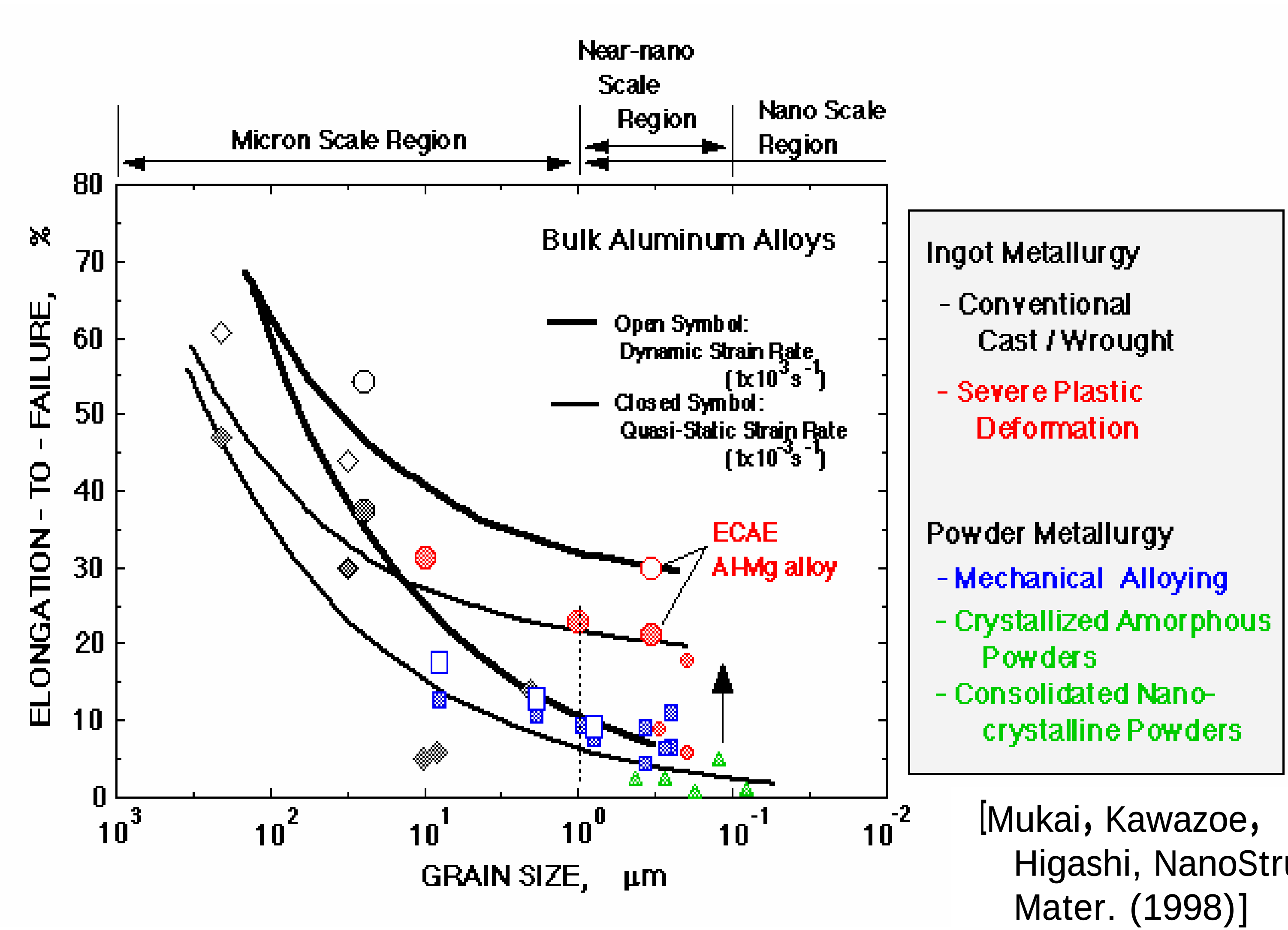
RCAST, Univ. Tokyo



[Mukai, Kawazoe, Higashi, NanoStruct. Mater. (1998)]

- Possibility of nano-crystalline/solid solution alloys

Purpose of this study

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RCAST, Univ. Tokyo

- To investigate the strain rate dependence of mechanical properties in nano-crystalline metal alloy
- To know the fracture behavior of nano-structured alloy
- Development of high-strength Al alloy with sufficient ductility in a wide range of strain rate

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Univ. Tokyo

Proposed Processing

- Ultra-high speed quenching (~ 10^{10} K/s) with Electron Beam Deposition - Vapor Quench(VQ) process.
- Composition controlled process with feedback
- Merit
  - Fabrication of super-saturated solid solution alloy

[Sasaki, Kita, Nagahora, Inoue: Mater. Trans, 42 (2001) 1561]

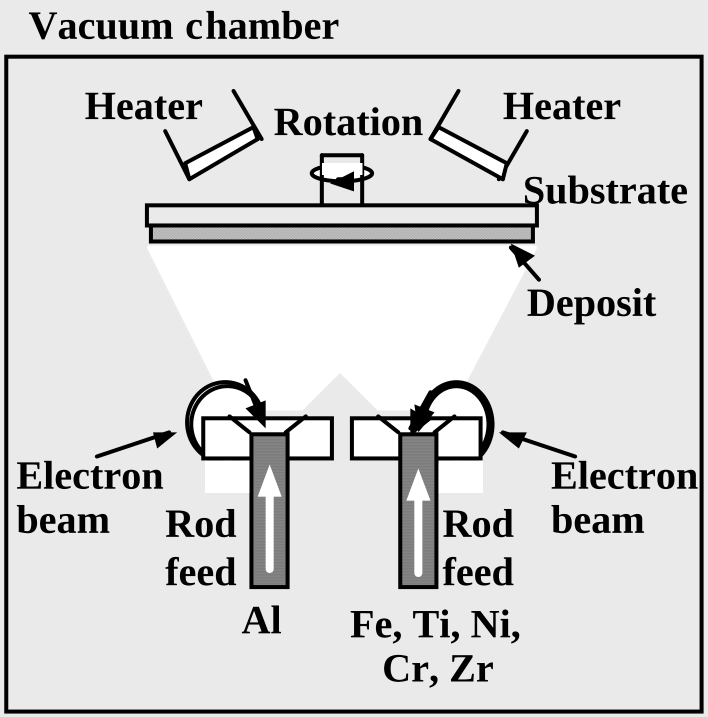

Fig. 1 Schematic diagram of continuous electron-beam evaporation setup.

Effect of Solute for Grain Refinement

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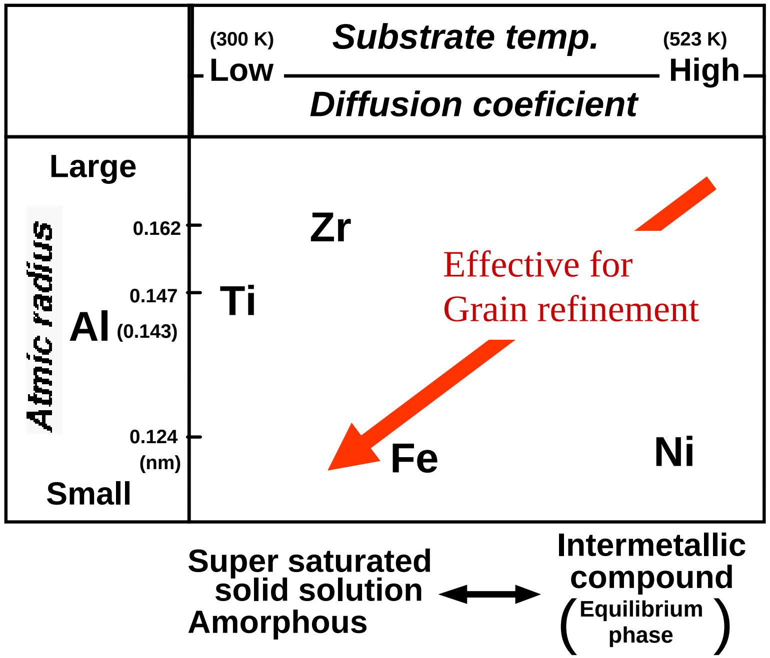
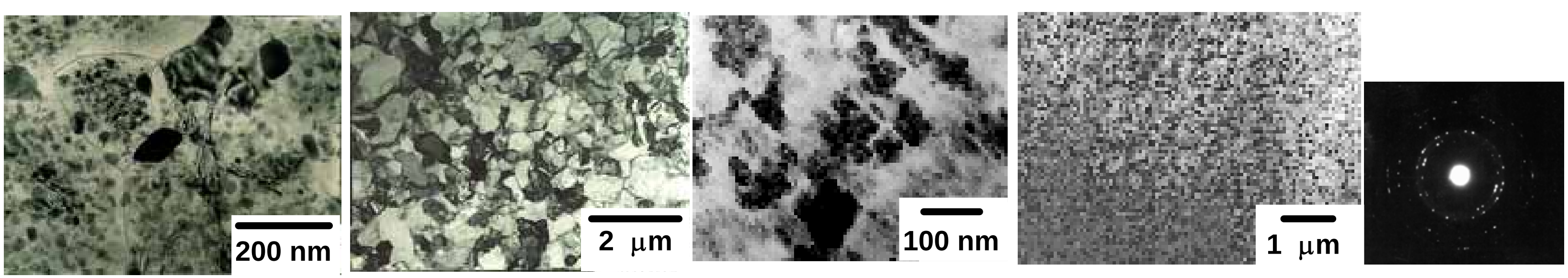
<u>Previous Trial</u>

- Atomic radius
- Diffusion coefficient

Ni: Easy to form the Equilibrium phase
Ti: Easy to coarsening grains
<u>Fe: Effective</u>

[Sasaki, Kita, Nagahora, (2001)]





$Al_{99}Ni_1$ $Al_{87}Ti_{13}$ $Al_{98.5}Fe_{1.5}$ $Al_{90}Fe_{10}$

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Microstructural Characterization of Vapor-Quenched Al-Fe alloys

Microstructure of VQ Al-Fe Alloy

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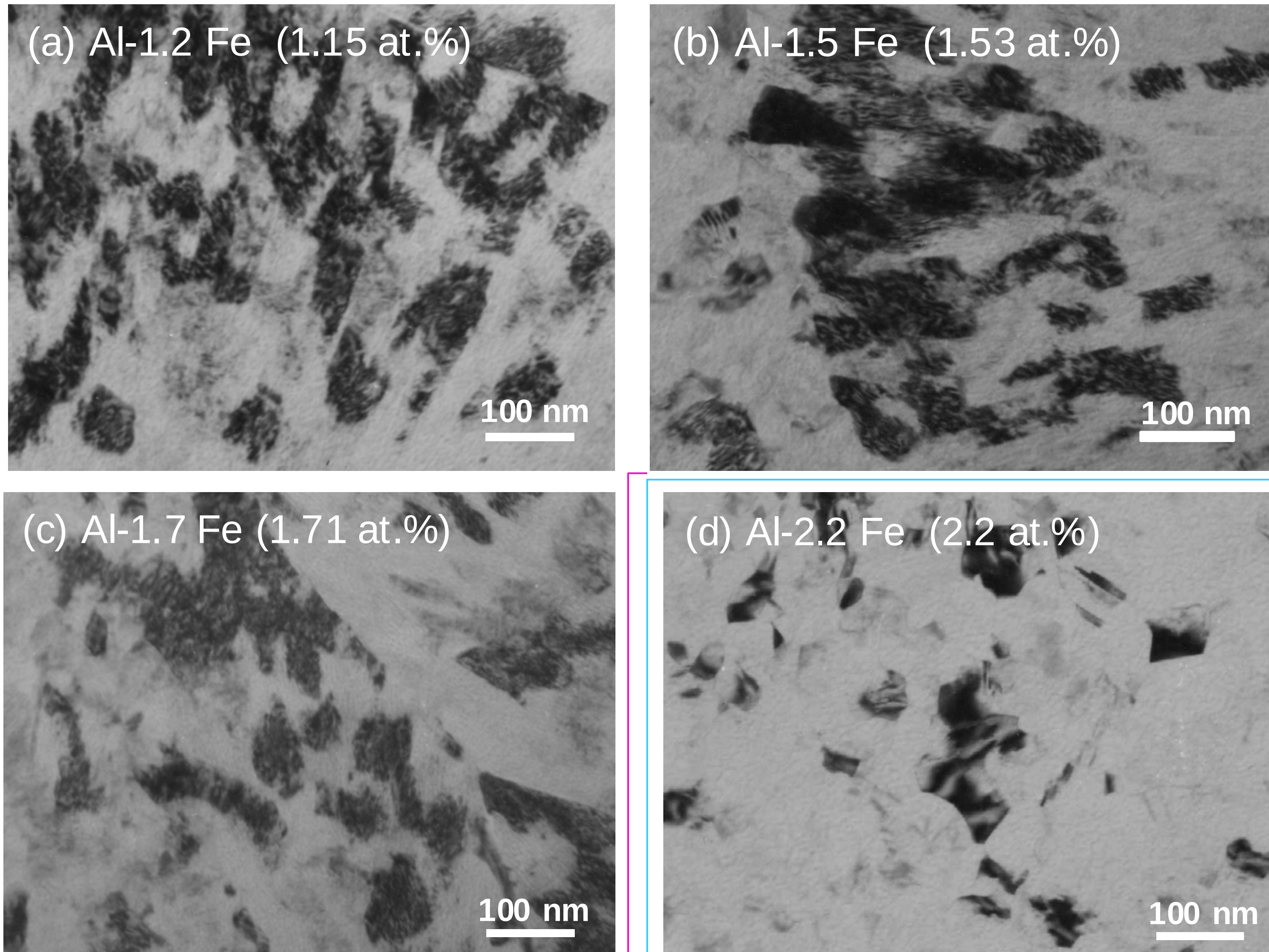
Univ. Tokyo



Selected Area Diffraction Pattern of Al-Fe Alloy

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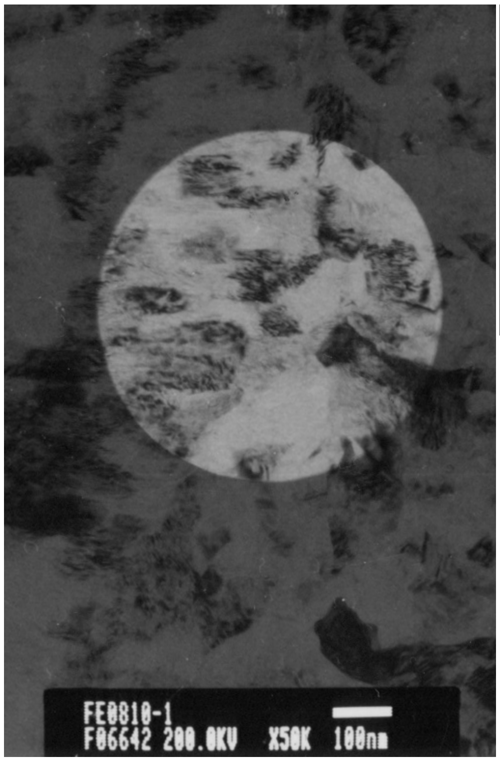
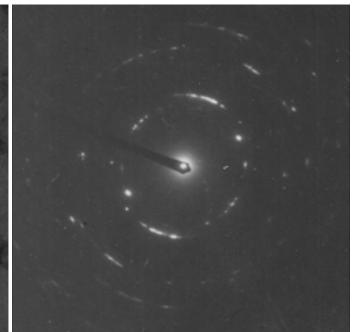
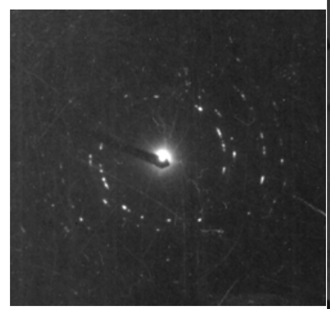
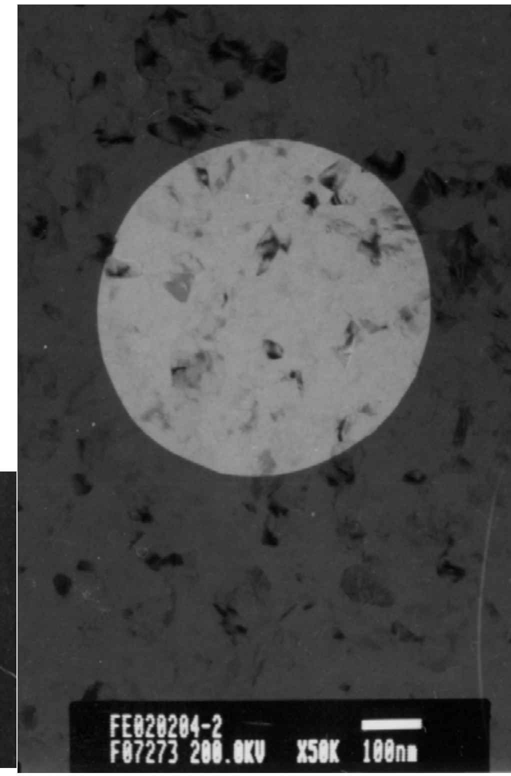
Al-1.5 Fe

Al-2.2 Fe









- Distribution of grain orientation

  --- Al-2.2 Fe alloy has larger distribution of orientation than Al-1.5 Fe alloy.

Al-Fe Super-saturated Solid Solution Alloy

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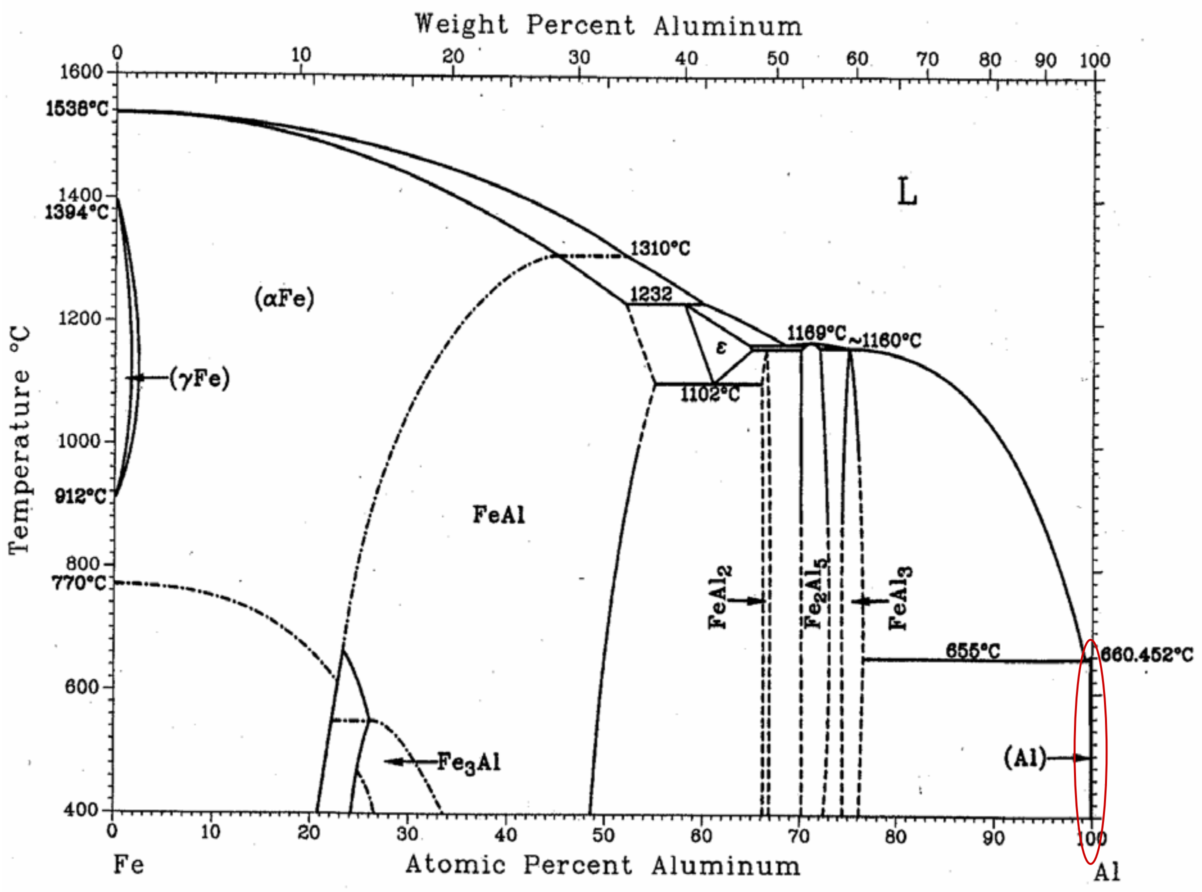

- Al solid solution: solubility of up to 0.03 at.% Fe in Al
- Vapor quenching technique enables to fabricate super-saturated solid solution alloy up to 3 at.% Fe.

X-ray Diffraction Pattern in VQ Al-Fe Alloys

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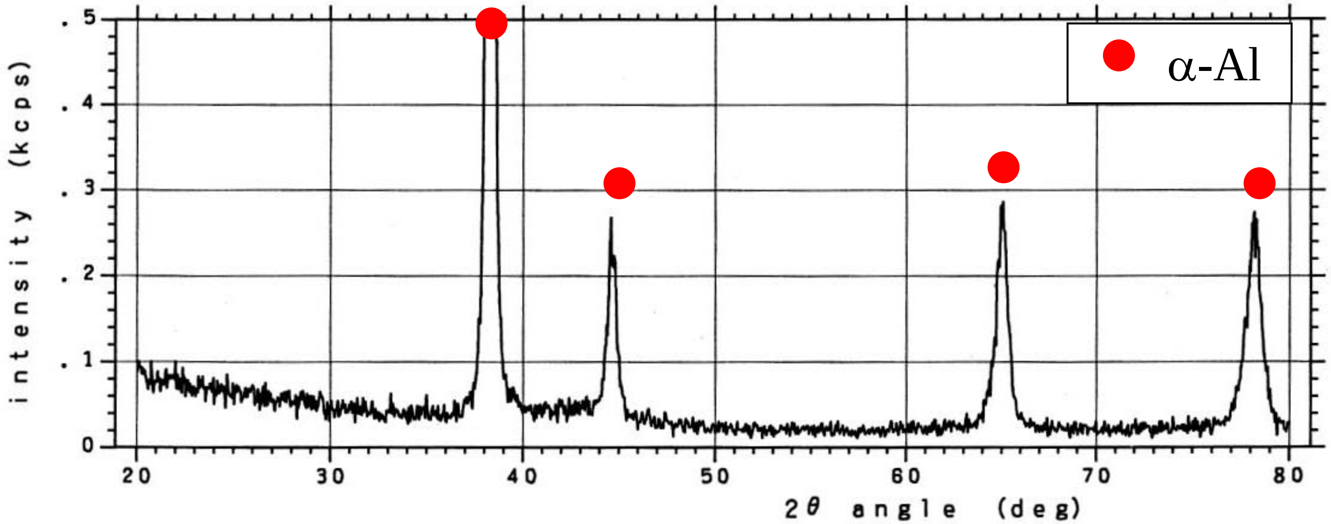
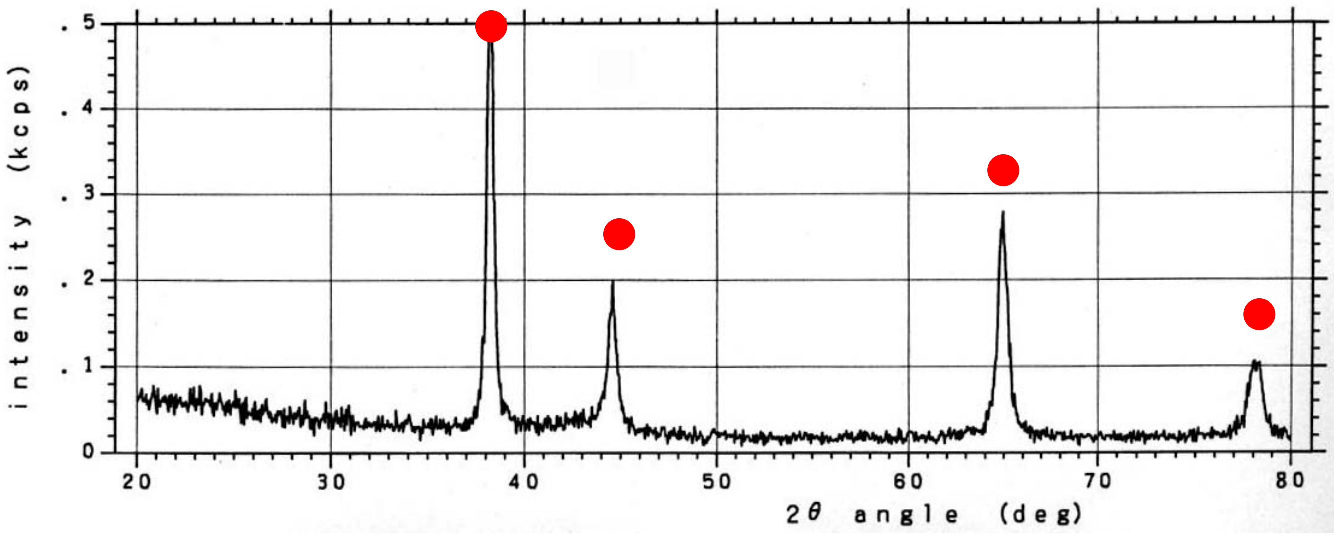


As deposited

Al-1.5 Fe



Al-2.2 Fe

- No second phase

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Mechanical Response of Nano-crystalline Al-Fe Alloys

Tensile Tests

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Schematic Illustration of Tensile Hopkinson-bar

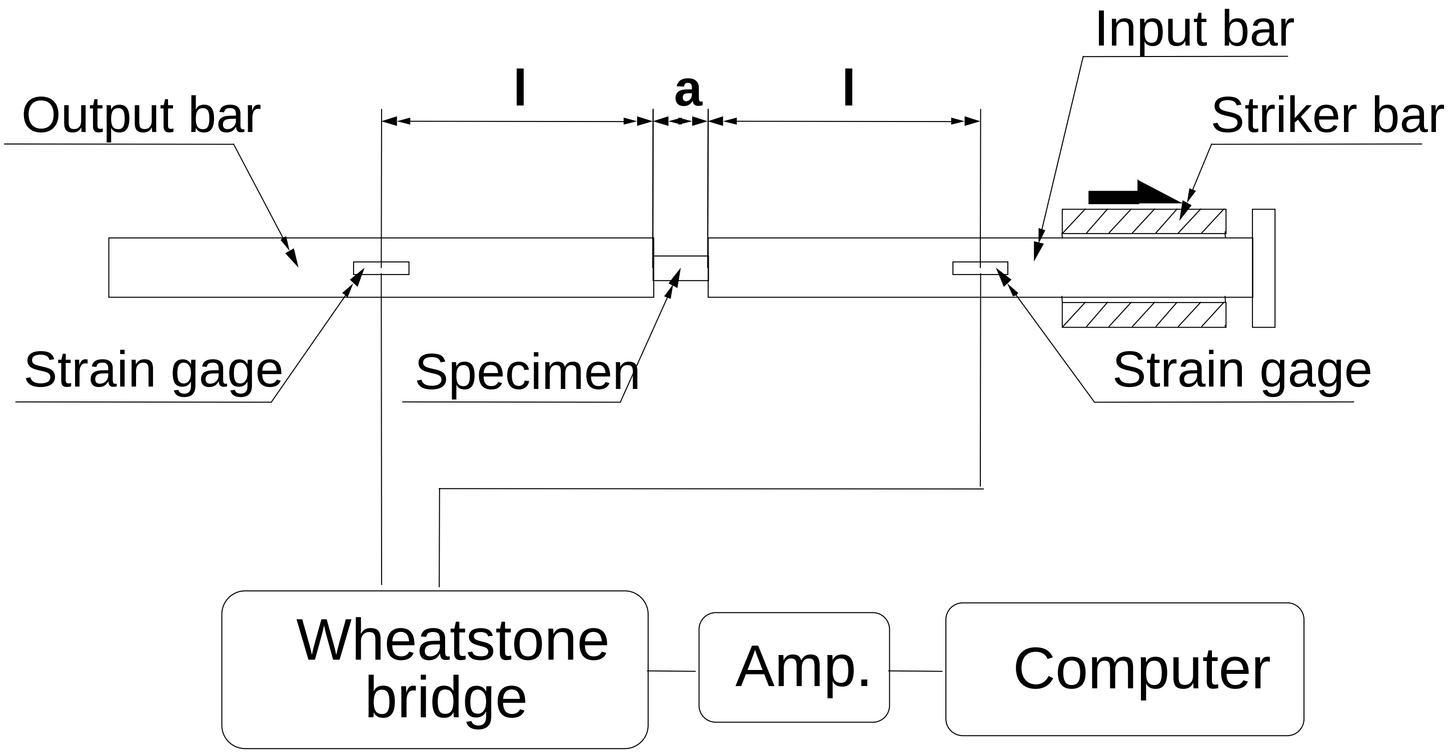

Plate Specimen (Dog-bone type)

- Dimension - Gauge length: 9 mm, width: 3 mm
  Thickness: 0.6 mm
- Strain Rate：1100 s^{-1} (Comparing with $1 \times 10^{-3} s^{-1}$)

Tensile Mechanical Response

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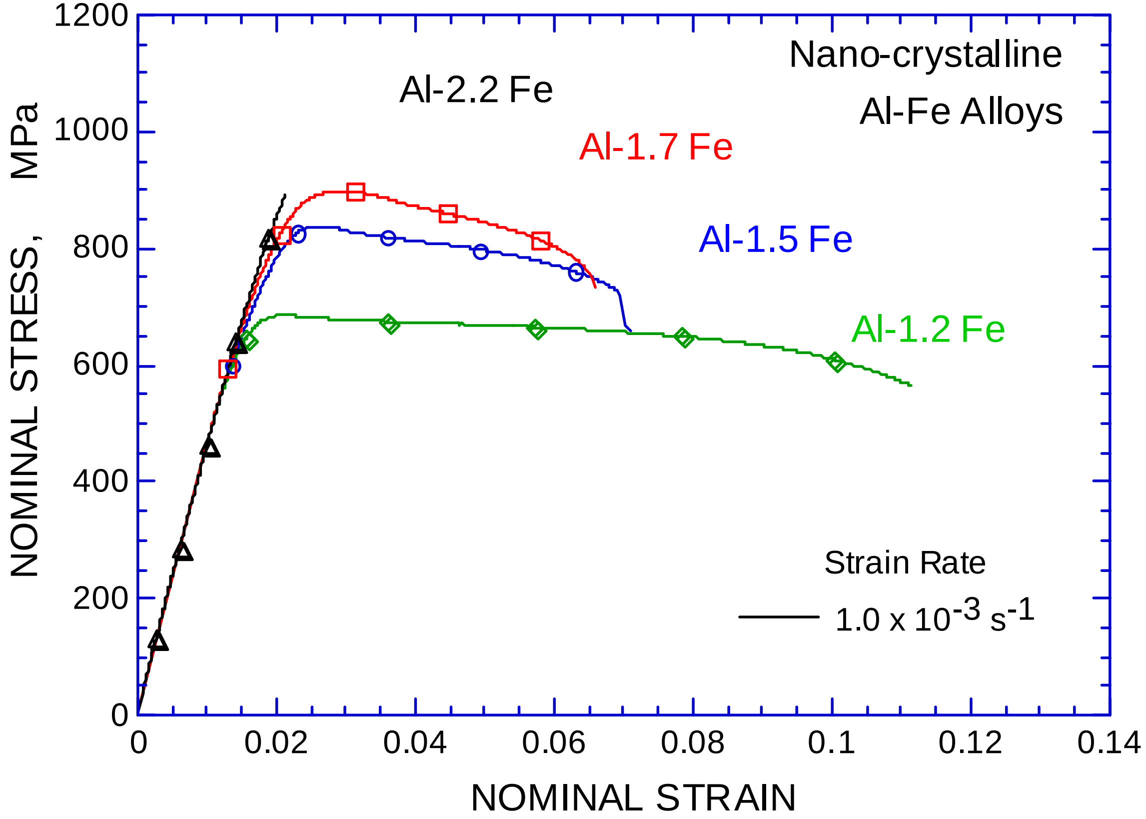

- Higher strength than conventional Al alloys.
- Strength increases and ductility decreases with increasing the content of Fe.
- Limited strain hardening

Tensile Mechanical Response

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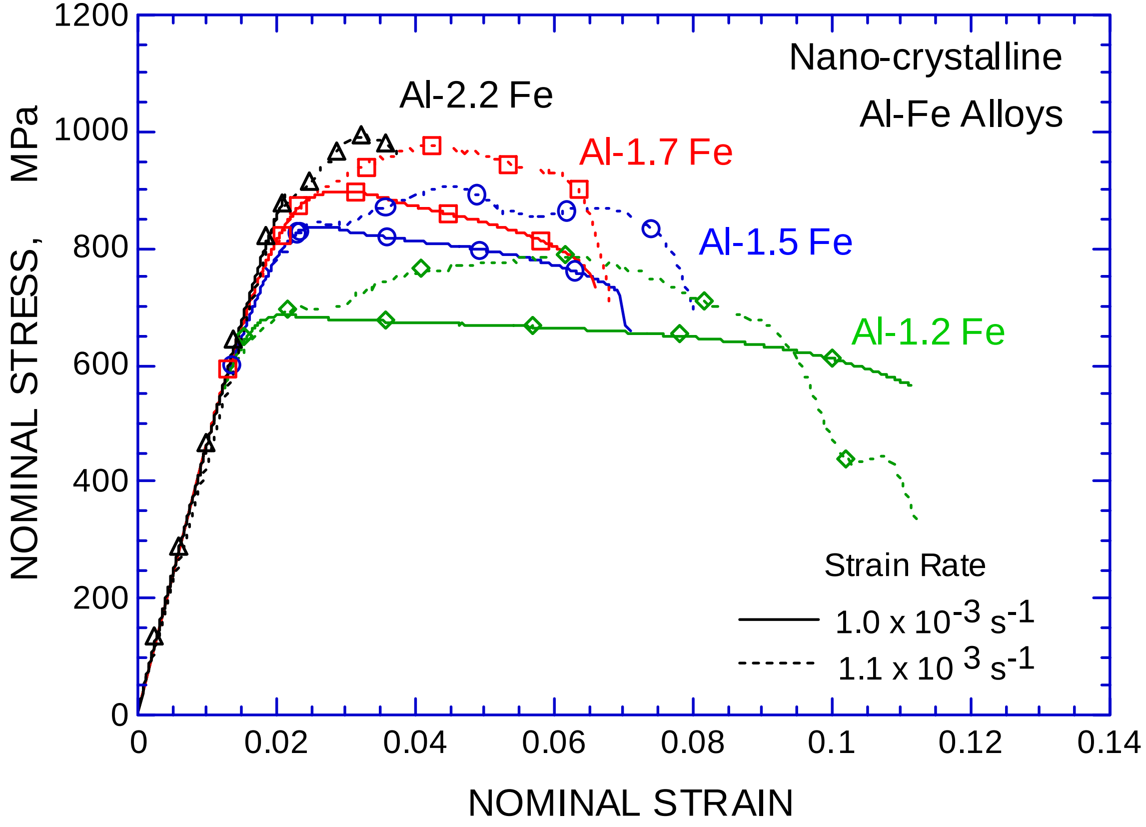
[Mukai, Suresh, Kita, Sasaki, Kobayashi, Higashi, Inoue: Acta Mater.,
-in press]



- Al-1.7 Fe alloy exhibits a high strength ~ 950 MPa with sufficient ductility more than 5% at a dynamic strain rate.
- Yield Stress is independent of strain rate, while flow stress and elongation-to-failure increase. The strain hardening rate is higher at the high strain rate.

Strain Rate Dependence of Yield Stress

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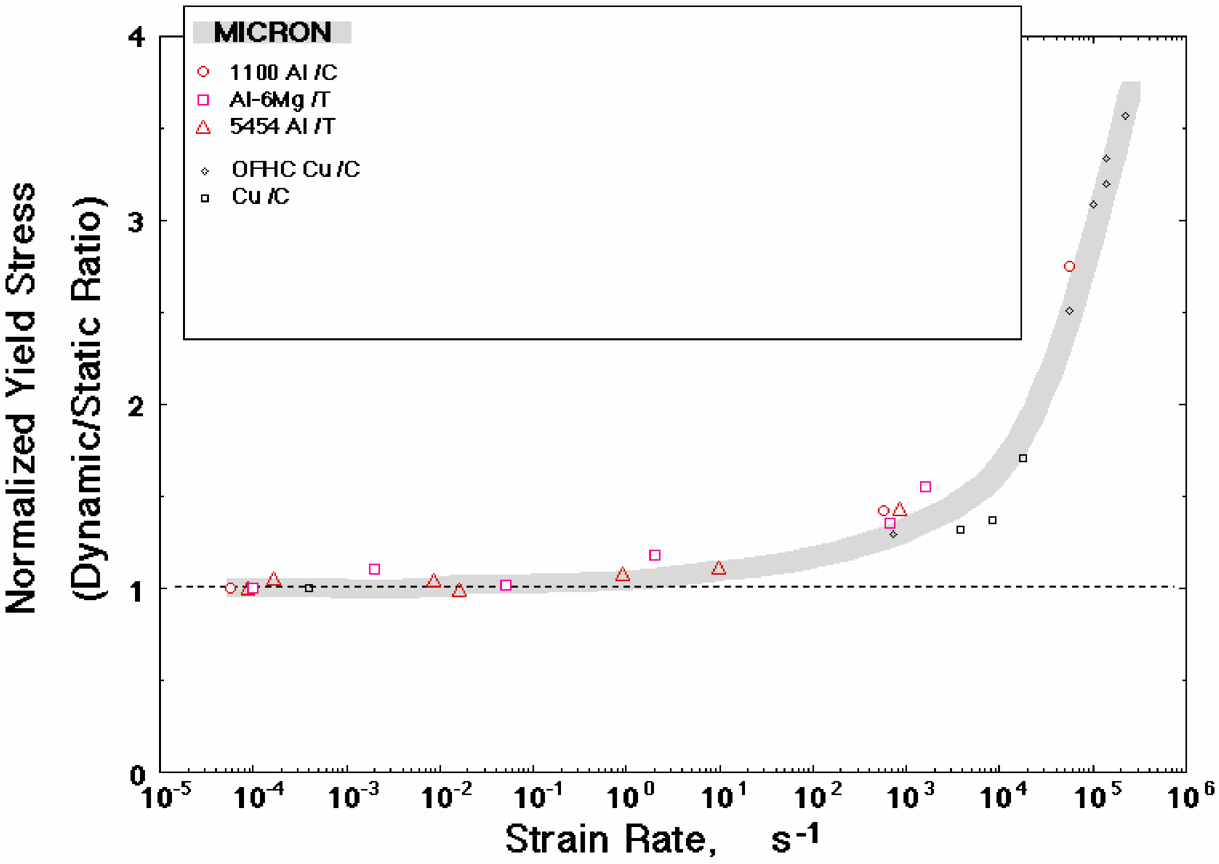

- Micron crystalline alloy shows progressive strain rate sensitivity.

Strain Rate Dependence of Yield Stress

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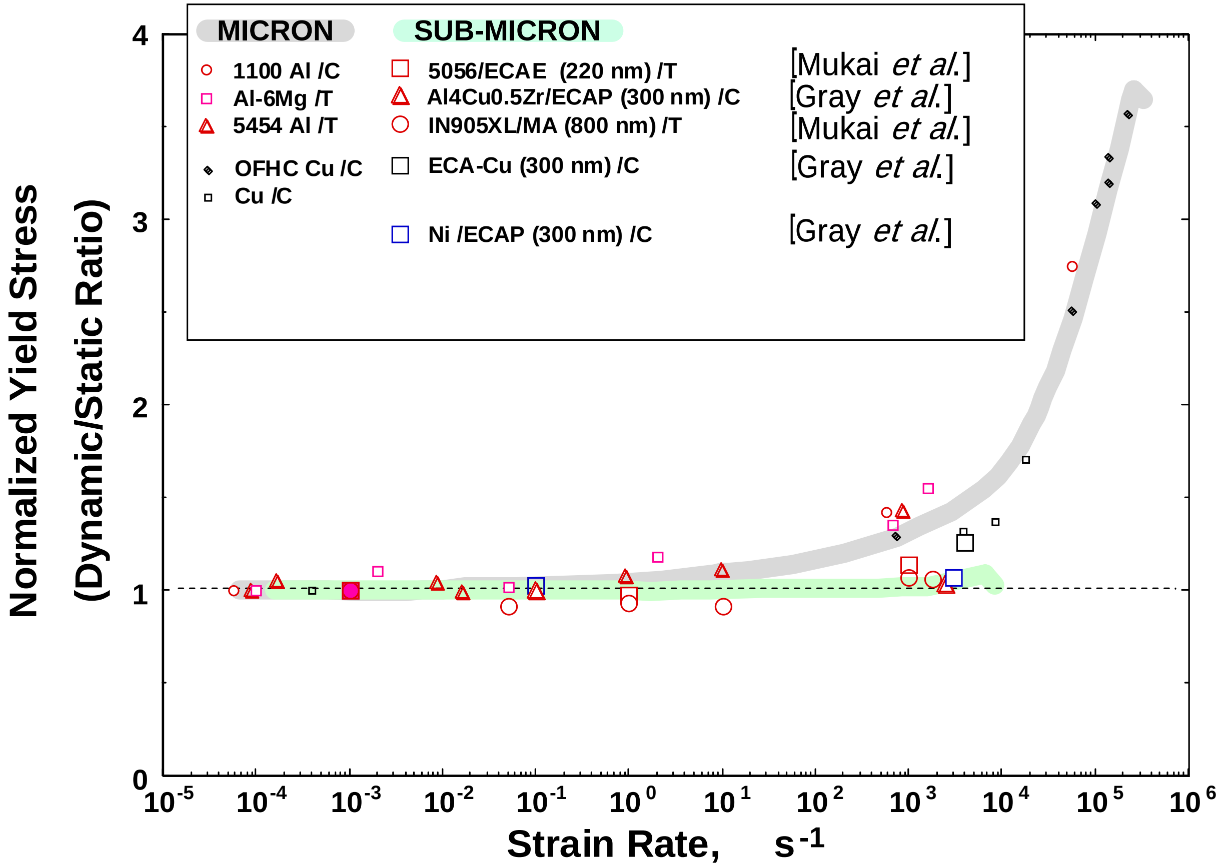

[Gray *et al.*, NanoStruct. Mater. (1997)]
[Mukai *et al.*, Met. Mater. Trans. (1995), NanoStruct. Mater. (1998)]

- Sub-micron-crystalline alloys exhibit low strain rate sensitivity.

Strain Rate Dependence of Yield Stress

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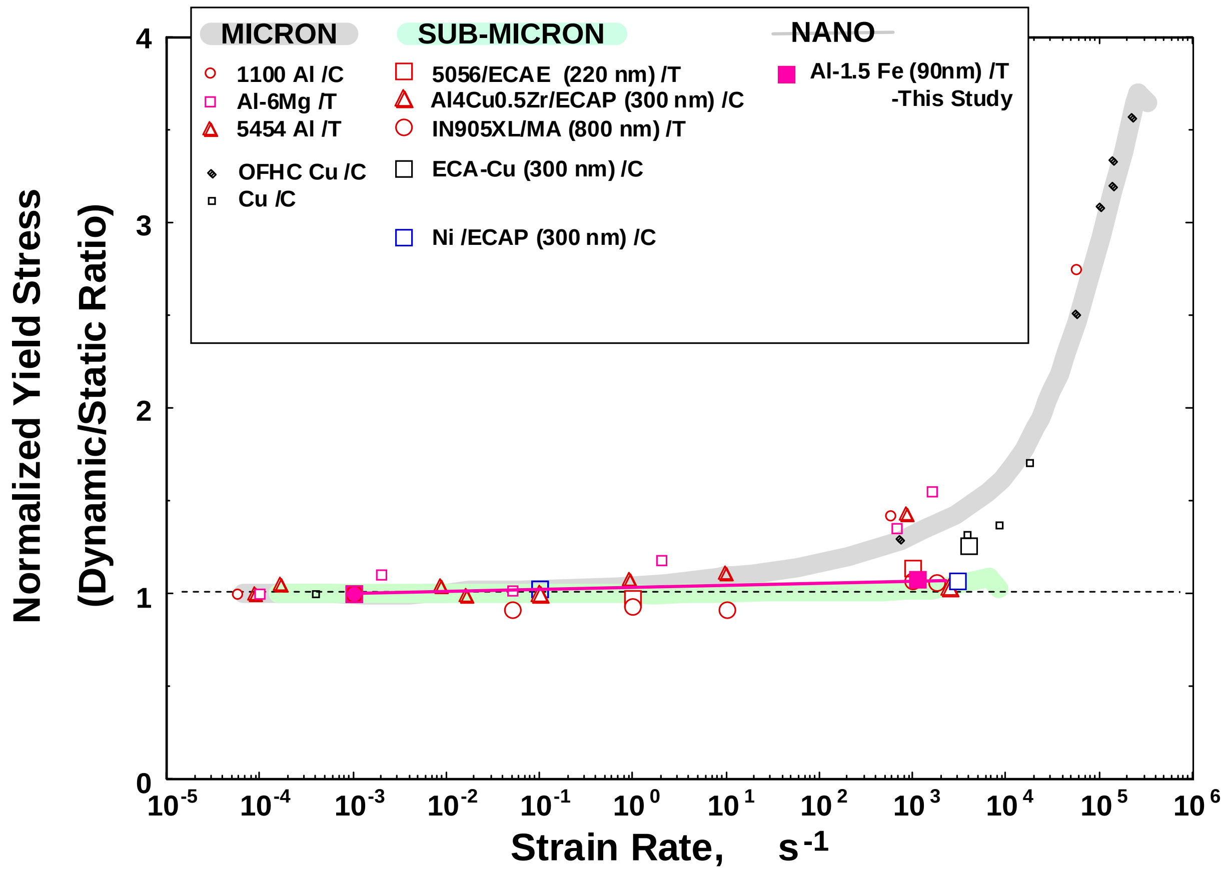

- Nano-crystalline Al-Fe alloy exhibits low strain rate sensitivity
- For ECAP or MM alloys, highly constrained dislocation network limits the strain rate sensitivity. Another microstructural factor also limits the strain rate sensitivity of yield stress for NC Al-Fe alloys.

Strain Rate Dependence of Yield Stress

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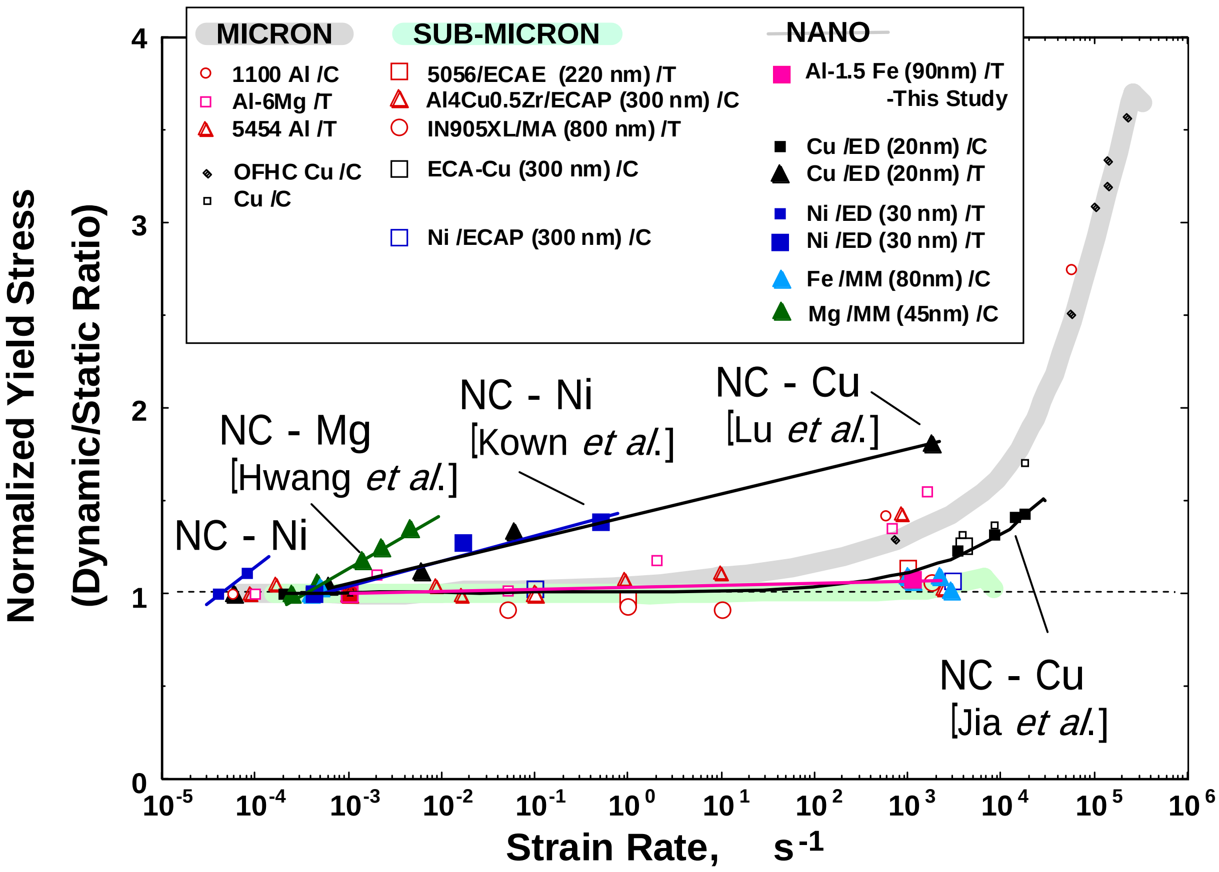

- Some nano-crystalline pure metals exhibit strain rate sensitivity owing to the dominant deformation mechanisms, I.e., GBS or Coble creep.

Tensile Mechanical Response

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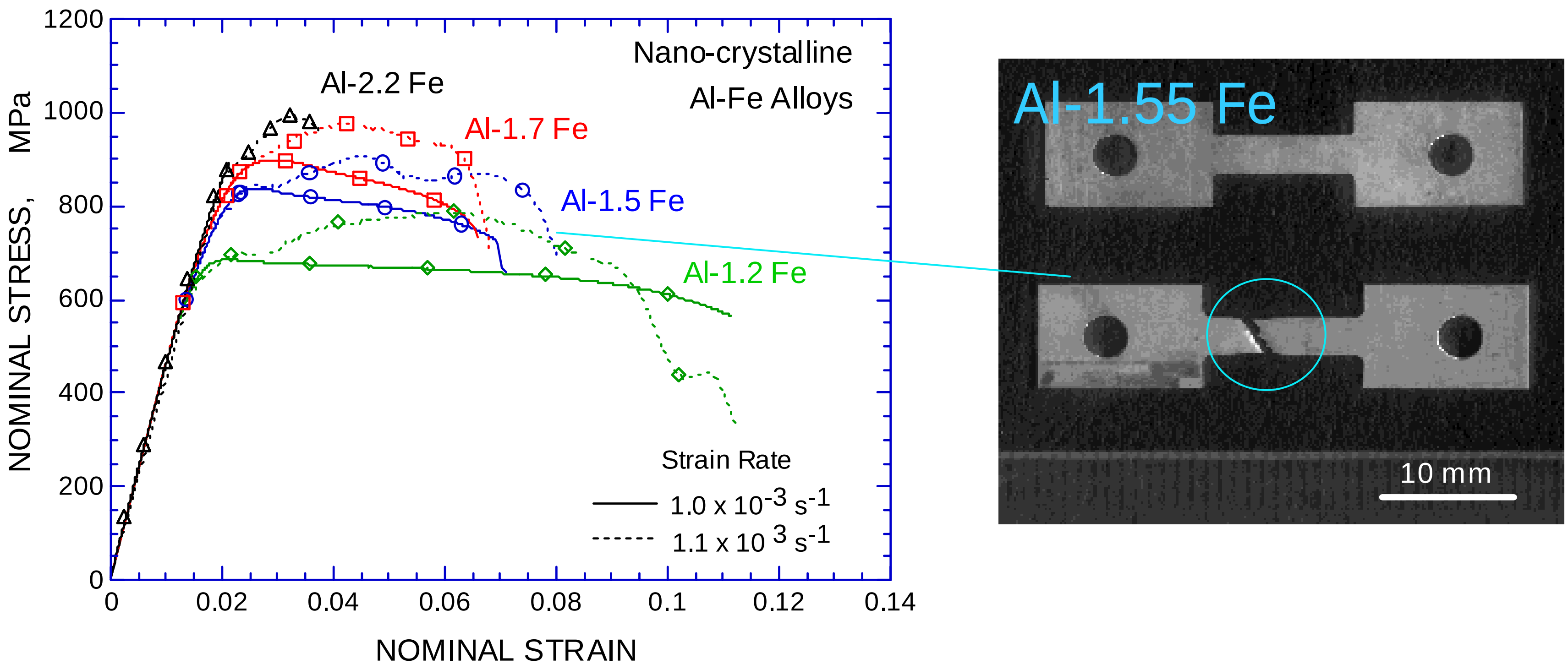

- Macroscopic fracture feature is noted to development of necking and formation of localized shear.

Fracture Feature of VQ Al-Fe Alloys

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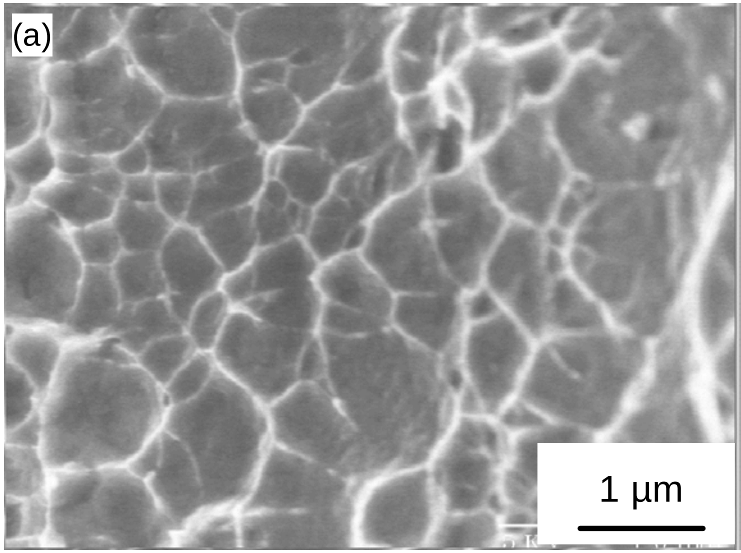
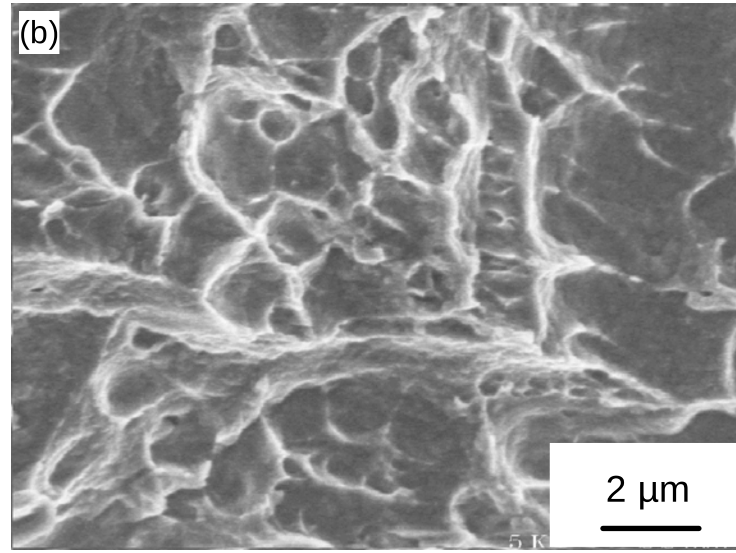
Al-1.7 Fe



Strain rate: $1\text{x}10^{-3}$ s^{-1}



Strain rate: $1.1\text{x}10^{3}$ s^{-1}

- Fracture surface typically consists of dimples.

  \>>> Evidence of dislocation motion interior of grains.

- Small and Shallow dimples at quasi-static strain rate suggest the limited ductility.

Evidence of Uniformly Distributed Nano-Defects

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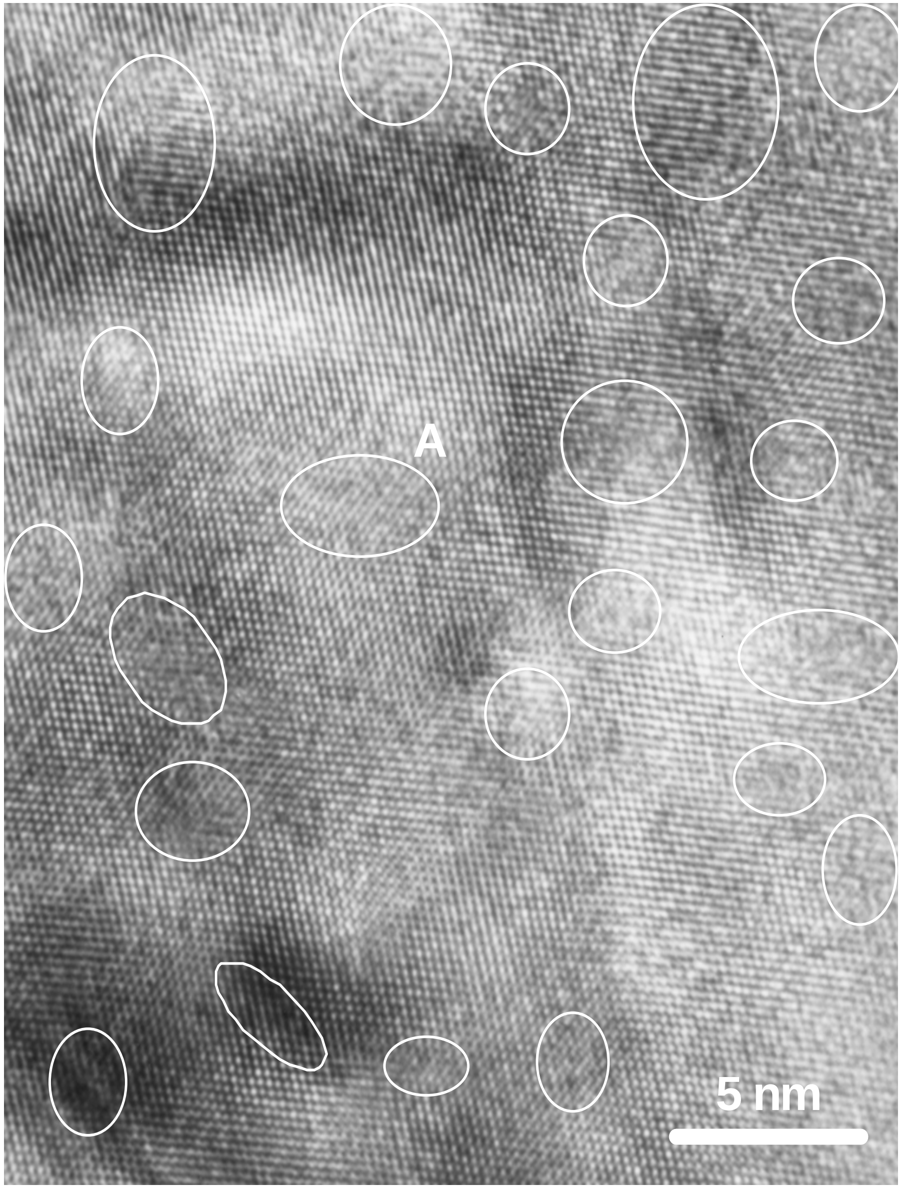
RCAST, Univ. Tokyo



Existence of Defect and Its Effect on Lattice Bending

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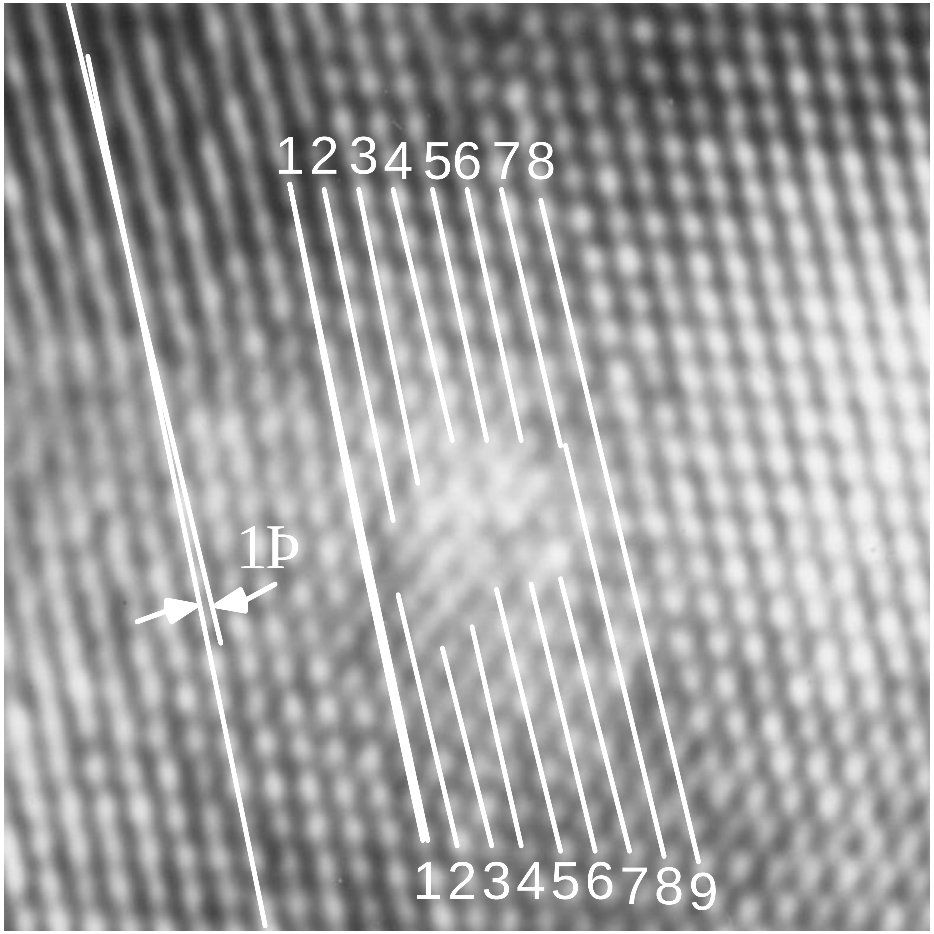

[Mukai, Suresh, Kita, Sasaki, Kobayashi, Higashi, Inoue: Acta Mater., *-in press*]

Influence of Concentration of Second Element on Strength in Binary Al Alloys

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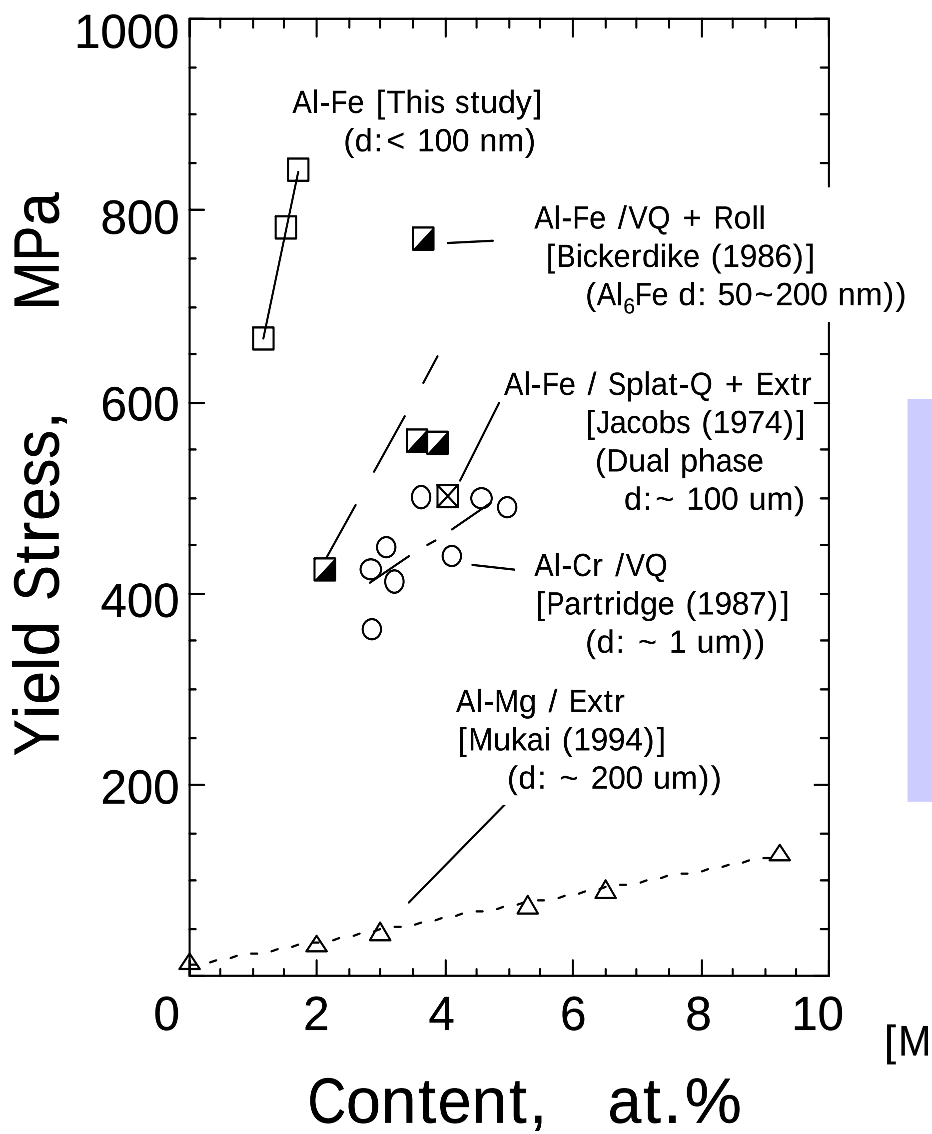

- Fe is effective element for strengthening.
- Strengthening rate is varied by its processing route.

[Mukai, Suresh, Kita, Sasaki, Kobayashi, Higashi, Inoue: Acta Mater., *-in press*]

SUMMARY

Toshiji Mukai
RCAST,
Univ. Tokyo

- Grain size of Al-Fe binary alloy was effectively refined with super-saturated iron solute. Formation of nano-crystalline structure was confirmed by TEM observation.
- Fine-grained Al-Fe alloys exhibit positive strain rate sensitivity of elongation-to-failure.
- The as-deposited Al-1.71 at.% Fe alloy showed an abnormal high tensile strength of ~950 MPa and sufficient ductility of ~ 5 % in tension at a high strain rate of $1.1\text{x}10^3$ s^{-1}.
- Fractography possibly suggests reduction of elongation in the nano-crystalline alloy with high angle grain boundary resulted in the intergranular fracture contrary to the the alloy with low angle grain boundary.